Optimal development of the future Danish energy system – insights from TIMES-DTU model

Stefan Petrović[a], Kenneth Karlsson[b], Olexandr Balyk[c]

[a] *Department of Management Engineering, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark.* stpet@dtu.dk
[b] *Department of Management Engineering, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark.* keka@dtu.dk
[c] *Department of Management Engineering, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark.* obal@dtu.dk

Abstract:

After a long period of transition, Danish energy system is half-way towards completely renewable in 2050. Drastic changes happened in the last forty years – the imported oil has been replaced by a mix of coal and natural gas, energy efficiency and conservation have been improved by extensive use of CHP-based district heating and heat saving measures. In the same period Denmark became well-known by integration and export of wind turbines. In line with the changes in the past, Denmark currently has very ambitious renewable energy targets, most ambitious being the 100 % renewable energy system in 2050. To achieve this, it is obvious that the present energy system needs to change, but the open question is how this should be done.
In order to answer this question, the present paper uses TIMES-DTU model. TIMES-DTU is technology-rich, bottom-up, optimisation model covering all sectors of the Danish energy system, assuming full foresight and perfect competition. It simultaneously optimises investments and operation across all sectors and all time periods. Three different scenarios have been described in the present paper: (i) Base scenario without any policy constraints imposed on the model, (ii) WLP with the constraint that 50 % of electricity production should come from wind starting from 2020, and (iii) WLP-NFE scenario with the constraint that power and heat sector should be fossil fuel-free starting from 2035 and Denmark should be 100 % renewable starting from 2050. In all scenarios, Denmark was constrained to be a net exporter of electricity.
The results imply that heat demand in future Danish energy system will be significantly reduced as a result of significant heat saving measures within the building stock, especially in rural and sub-urban areas. In urban areas, large district heating networks will supply between 55 and 73 % of heat supply in the years close to 2050. Electricity demand will be largely increased mainly due to transition to large scale heat pumps in the district heating networks. More than 90 % of increased demand for electricity will be based on on-shore and off-shore wind energy. WLP scenario implies less than 1 % higher total system costs compared to Base scenario, while WLP-NFE scenario implies 5-6 % higher total system costs compared to Base scenario. An additional conclusion from the current study is that Denmark has sufficient resources to achieve self-sufficiency in energy supply.

Keywords:

Energy system modelling, TIMES model, energy system planning, energy conservation, renewable energy system.

1. Introduction

If a "snapshot" of the Danish energy system from before the First Oil Crisis in 1973 is analysed, it can be concluded that it has been heavily changed in the last 40 years. Power and heat sectors have been converted from inefficient, environmentally harmful sectors based on oil to efficient sectors based on renewable energy, coal and natural gas. As a result of that, share of renewables in electricity production changed from 0 to 46 %, share of renewables in district heating production from 0 to 20 % while share of renewables in individual heating changed from 0 to 43 %. District heating based on waste heat from CHPs (Combined Heat and Power) and energy conservation measures within the building stock proved to be important components in the process of improving the overall system efficiency during the period. Even though total heated area of buildings has increased by more than 50 % [1], primary energy consumed for heating decreased by more than 30 %. In the same period, district heating share increased from 28 % to 54 % [2]. The increase in renewable energy shares in transportation sector was much less pronounced; it increased from 0 to 4.3 % in the whole sector corresponding to the growth from 0 to 5.7 % in the road transport. The share of electricity reached 0.7 % of the final energy consumption in the transportation sector in 2013 or around 30 % of the train transport. Final energy consumption in the transportation sector was increased by 50 % over the 40 year period, mainly due to increase of 72 % in the road transport [2]. Residential, power and heat sectors have already proven to have a ready set of solutions for fulfilment of long term goal of the Danish Government of being 100 % renewable no later than 2035 [3]. On the other hand, new solutions are needed to reduce energy consumption in transportation sector and switch to renewable fuels.

Despite putting a specific focus on different parts of the system and different periods in the future, energy system models have been used in recent years to explore how the Danish energy system as a whole should develop. The role of district heating in the Danish energy system was analysed in [4] for year 2025 and years 2020 and 2060 in [5, 6]. The influence of excess heat production from NZEBs (Net Zero Energy Buildings) on the district heating system in year 2050 was addressed in [7]. Special emphasis in renewable energy scenario for Aalborg Municipality in year 2050 was put on low-temperature geothermal-based district heating system [8]. Influence of residential heat pumps on wind power integration has been analysed in [9-11]. Short-term effects of heat savings and district heating expansion on local energy system of Frederikshavn have been documented in [12], while medium and long-term role of heat savings in buildings in the Danish energy system have been analysed in [13, 14]. Different energy systems in different years were used as case studies for analysis of transportation sectors: Danish in 2030 [15], Finnish in 2035 [16], Nordic in 2050 [17] and North European in 2030 [18] and from 2015 to 2030 [19]. The optimization of waste treatment in the Danish energy system from economic perspective was performed in [20], while both environmental and economic dimensions have been accounted for in [21]. Models of the Danish energy system were also utilised for analysis of topics partly falling within other parts of society, such as health-related externalities [13, 22], climate mitigation and economic growth [23] and limiting the use of biomass [24]. Majority of the analysis have been performed using two models: Balmorel [4, 9, 10, 13-20, 22] and EnergyPlan [5, 6, 8, 11, 12, 23, 23].

In several other countries, energy system models belonging to TIMES family have been in use for many years. Irish TIMES model was used for analysis of national energy security [25], short-term [26] and long-term GHG emission targets [27], improving representation of the power sector in the long-term energy system models [28], etc. Several TIMES models were used in Germany for analysis of decentralised heat supply [29], economic potential for thermal load management [30], impacts of prescribed efficiency improvement measures [31], interaction between emission trading and renewable electricity support [32], etc. TIMES-Norway was used to evaluate possible ways for Norway to fulfil the RES directive [33] and to study the impact of future energy demand on the energy system [34], while [35] and [36] described the future of nuclear power in Switzerland and France, respectively.

This paper presents methodology and results of the analysis of the Danish energy system until 2050. Three main scenarios have been examined within TIMES-DTU model to answer the following questions: What is the optimal supply configuration of the future Danish energy system under renewable energy targets? Which fuels should be used in the future? What is the role of efficiency measures? How much does it cost to convert the energy system to renewable energy and how does it affect the environment?

2. TIMES models

The short description of the TIMES models is based on authors' experience in working with TIMES models and references [37-41].

TIMES (an acronym for The Integrated MARKAL-EFOM System) was developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP), an Implementing Agreement of the International Energy Agency (IEA), established in 1976. TIMES is a multi-regional, technology-rich, bottom-up model generator used for long-term analysis and planning of regional, national and multi-national energy systems. In addition to that, TIMES is a techno-economic, partial equilibrium model-generator assuming full foresight and perfectly competitive markets. It is usually utilised for simultaneous analysis over a whole energy system, but can be also used for analysis of specific sectors.

Four types of inputs are defined by the user in TIMES models: demand curves, supply curves, policies and techno-economic parameters. Supply curves are showing the quantities of primary energy resources (such as wind power) or imported commodities (such as electricity) available and demanded at a specific cost. The techno-economic parameters are assigned to currently available and future technologies (called process in TIMES) that are converting one or more commodities into one or more other commodities (for example, oil boiler transforms oil into heat and CO_2). The examples of technical parameters are efficiency and availability factor, while economical parameters include investment costs and interest rates. The policies include effects of legislation, taxes, incentives, etc. and thus change the optimal solution for the analysed energy system. The example of a policy constraint is the Danish target of being 100 % renewable no later than 2050. The user also specifies the properties of existing stock of technologies in the base year.

Using the inputs, TIMES optimizes investments, operation, energy supply and import/export over all regions and all time periods. The outputs from the model include region and time-specific investment, operation and import/export levels optimal for the energy system as a whole. In addition to that, the costs, environmental indicators, prices of commodities, etc. are obtained alongside the optimal solution.

The basic elements of any TIMES model are: processes, commodities and commodity flows. Commodities consist of energy carriers (such as oil or biomass), energy services (transported ton of freight), materials (for example reserves of natural gas), monetary flows (DKK, USD …) and emissions (CO2, CH4…). Processes are "converters" from one or more commodities into one or more different commodities. Commodity flows are the links between processes and commodities. A commodity flow has the same nature as a commodity but is attached to the particular process, and represents one input or one output of that process.

3. TIMES model for Denmark

The first fully-working version of TIMES model for Denmark , including residential, power and heat and transportation sectors, is developed by Energy Systems Analysis group, DTU Management Engineering, E4SMA and the IntERACT team from the Danish Energy Agency. All of the authors of the current paper have been members of the project team. For detailed description of TIMES-DTU model, the reader should consult model documentation at www.ens.dk/interact.

3.1 Geographical and temporal definition

Denmark is divided into two regions – East and West Denmark. These regions will be denoted with DKE and DKW throughout the paper. These regions are electrically connected by 600 MW HVDC cable, while demand and supply of heat need to be balanced within each of the regions.

Time is represented in the form of time-slices without established chronology. Time-slices represent hours with similar characteristics within the same year. The 32 time-slices in TIMES-DTU resulted from the aggregation of periods with specific hourly values:

- Four seasons in a year,
- Two periods in a week – workday and weekend,
- Four critical situations in the Danish power system:

- Wind power is high, while power demand is low. There is a risk of excess electricity production in these periods which could result in low power prices and need for wind curtailment or export.
- Wind power is low, while power demand is high. There is a need for import or backup capacity in these periods.
- Peak PV production. There is a risk of excess electricity production in these periods which could result in low power prices and need for export.
- Remaining time periods.

Time-slices have different lengths, ranging from 1 hour in case of time-slice covering winter workdays with high wind power and low power demand up to 1409 hours in case of time-slice covering workdays in autumn classified as "Remaining time periods". One or more years are grouped into time-periods. The lengths of time-periods vary from one to five years and are longer if they are closer to the end of the analysed period, as showed in Table 1.

Table 1. Length of time-periods in TIMES-DTU

Time period	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Start year	2010	2011	2014	2018	2023	2028	2033	2038	2043	2048
End year	2010	2013	2017	2022	2027	2032	2037	2042	2047	2052
Length (years)	1	3	4	5	5	5	5	5	5	5
Representative year	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050

3.2 Energy resources and trade

TIMES-DTU uses domestically available and imported, renewable and non-renewable resources for production of electricity, heat and transport work in the energy system.

For non-internationally traded fuels, their domestic potentials were specified in the model. Domestically available onshore and offshore wind and wave potentials were obtained from [42], while domestic PV, solar thermal and geothermal potential were obtained from [43]. The domestic potentials of straw, woodchips, wood waste and slurry were based on [44].

Domestic waste potentials were obtained from FRIDA model [45] and TIMES-DTU was forced to incinerate the entire potential in all analysed scenarios. The long-term price projections for straw, woodchips, wood waste and slurry were obtained from [46]. For internationally traded fuels, long-term price projections have been obtained from [47] and their import was not constrained in the model.

Electricity trade with neighbouring countries was enabled in TIMES-DTU. Connections have been represented with capacities (in MW) and import/export price projections (DKK[1]/MWh) from/to each of the neighbouring countries. The price projections, existing capacities and planned extensions of transmission capacities have been adopted according to [48].

3.3 Power and heat sector

Power and heat sector in TIMES-DTU is responsible for producing electricity and district heat in the model. Consumers are supplied with electricity and district heat via the transmission and distribution networks. State of the energy system in the base year is described with the number and installed capacities of facilities and grouped by size, type and geographical region. Retirement profile (share of the base year stock that will be decommissioned in each of the time periods) was specified for each group. The data about existing stock were obtained from [49, 50].

Each of the existing production facilities was represented in the model with following parameters: efficiency, fixed and variable O&M costs and availability factor. The techno-economic parameters

[1] DKK denotes Danish Crown. (1DKK=0.134 EUR)

used for describing the existing stock were obtained from [51]. The capacities of existing DH[2] grids in the base year were obtained from [52]. The electrical grid within DKE and DKW regions was described only with efficiencies, i.e. it is assumed that sufficient grid capacity is always available. In addition to parameters used for modelling of existing stock, new technologies are described by investment costs. Ref. [51] was used as a source of data techno-economic parameters for new technologies.

3.4 Transportation sector

Energy consumption of the transportation sector is endogenous in the model. The sector comprises two types of transport work i.e., passenger transport and transport of freight. These are delivered by the following modes: rail, road, aviation and ship transport. Vehicle stock is represented explicitly for both road and rail transport. There is a possibility for fuel switch and efficiency improvement in the sector. The transport sector is largely based on data from Statistics Denmark.

3.5 Residential sector

Residential sector in TIMES-DTU represents energy demand of Danish residential buildings. The data about buildings in the base year were obtained from the BBR dataset [53]. Net demand for space heating and domestic hot water for 360 groups of buildings was calculated based on the methodology presented in [54] and aggregated according to construction period (buildings built before 1972, after 1972 and new buildings), building type (Single-family and Multi-family buildings) and region (DKE and DKW). Electricity consumption of household appliances and their lifetimes were obtained from "Elmodelbolig" survey.

After the base year, heat demand in the residential sector is driven by the change in the heated area of buildings. Demolition rate of 0.5 Mm^2 per year and construction rate of 3 Mm^2 per year is assumed. The construction and demolition rates are distributed across the building stock proportionally to ratios in the base year. The electricity demand in the residential sector is driven by the assumed increase in number of electrical appliances and their efficiency.

There are two options for heat supply and one option for electricity supply of buildings – heat can be delivered from district heating system or individual heating technologies, while electricity can only be produced centrally in the system and transmitted to consumers. Residential heat demand can be reduced by heat saving measures.

In TIMES-DTU, district heating areas are grouped into Central and Decentral, according to the classification of DH plants in [49]. Central DH areas are usually based in bigger cities, have higher installed capacities, higher number of consumers and higher efficiencies compared to Decentral DH areas. Accordingly, residential buildings located within or close to Central DH areas belong to Central group, while buildings within or close to Decentral DH areas belong to Decentral group. Buildings located far away from existing DH areas belong to Individual group. For each of these building groups, potentials and costs of heat saving measures are defined according to methodology presented in [55].

3.6 Other sectors in TIMES-DTU

Besides residential, power and heat sector and transportation sector, TIMES-DTU includes six other sectors: Private Service, Public service, Construction activity, Manufacturing, Agriculture and Other sectors. These sectors are represented with inelastic demands for electricity and district heating which were adopted from DEA's (Danish Energy Agency's) Baseline Scenario from October 2012 [56].

4. Analysed scenarios

Three scenarios have been developed for the Danish energy system until 2050:

---

[2] DH denotes district heating throughout the paper.

- Base – No policy measures or renewable energy targets are being implemented.
- WLP (Wind Low Production) – Starting from 2020, at least 50 % of Danish electricity consumption needs to be produced from wind power [57].
- WLP-NFE (Wind Low Production–Non Fossil Energy) – In addition to WLP scenario, fossil fuels must not be used for power and heat production starting from 2035 and starting from 2050 energy system should be 100 % renewable [58].

Base scenario shows how the Danish energy system would look like solely as a result of minimization of total system costs. The comparison between WLP and Base scenario shows how the optimal configuration changes when significant amount of intermittent power production from wind needs to be balanced. In this scenario, the "traditional setup" of the energy system can be maintained without significant increase of total system costs – fast-reacting fossil-fuel-based units can provide backup for wind production, while waste heat from CHPs can be used for district heating. The only way to maintain the "traditional setup" in WLP-NFE scenario would be to use imported electricity, biomass or waste. However, relying on imported electricity, biomass or waste cannot be justified from the security of supply point of view. For that reason, in all scenarios, Denmark needs to be a net exporter of electricity and use only domestically available biomass and waste.

5. Results

The results are divided into the future of electricity and heat supply, future costs and future environmental emissions until 2050 for Base, WLP and WLP-NFE scenario.

5.1 Electricity and heat supply

The heat delivered to residential consumers is presented in Figure 1, while production of district heating which is being transmitted and distributed to all sectors is presented in **Erreur ! Source du renvoi introuvable.**. In Base scenario, TIMES-DTU model bases future heat supply mostly on district heating. Even though the heat delivered to households in 2050 is only 3% higher compared to 2010, share of district heating increased from 56.1 to 76.3 %. In the same period, amount of heat delivered by individual heating solutions decreased almost three times as a result of heat saving measures. There are two reasons for very high shares of residential heat demand being supplied by district heating – inexpensive coal and waste-based DH and inexpensive heat saving measures compared to individual heating solutions. Residential heat supply in WLP scenario is also mainly based on DH and it increases to 73 % in 2050. DH is mainly produced from waste and coal. In the transition period, from 2015 to 2040, between 5 and 22 % of district heating is produced by large-scale heat pumps. This is the result of the constraint that at least 50 % of electricity needs to be produced from wind power starting from 2020 – efficient production of district heating is found to be the most cost-efficient alternative. After 2035, export of electricity becomes most cost-efficient alternative. In WLP-NFE scenario DH remains favourable mean of supply, as it covers between 56 and 62 % of residential heat demand. Heat delivered from Central DH decreases by 14 %, but its share in total delivered heat increases from 36 to 43 %. However, Decentral DH losses its competitiveness in this system setup and covers only 14 % of demand in 2050. TIMES-DTU chooses large heat pumps before 2035 for the same reason as in WLP scenario, but "No fossil fuels after 2035" constraint limits fuel choices for DH production after 2035 to waste, biomass or electricity. Due to high costs and limited biomass potentials, waste incinerations and large scale heat pumps are selected. In all scenarios heat saving measures are utilised as inexpensive solutions for reducing heat demand, especially in Single-family buildings built before 1972 in Individual areas.

The production, export and import of electricity are presented in Figure 3. In Base scenario majority of domestic electricity production comes from coal-based Centralized CHPs. Its share grows from 2010 and reaches 86 % in 2050. The remaining share is being produced from onshore wind. Due to relatively low electricity prices compared to surrounding countries, Denmark exports between 42 and 47 % of its domestic production. In WLP scenario, the model utilises entire onshore wind potential already in 2020 and after that invests in offshore wind mills. At the end of analysed period, offshore wind makes 43%, onshore wind 13% and Centralized CHPs 44 % of total domestic production. In this scenario Denmark also acts as big exporter of electricity. In WLP-NFE scenario, effects of renewable energy targets in 2020 and 2035 are visible from the base year – the model heavily invests in onshore and offshore wind, while it doesn't invest in coal-based CHPs. The electricity production after 2035 is based only on wind power. Since the entire onshore wind potential is utilised in 2030, all investments after 2030 are made into offshore wind mills.

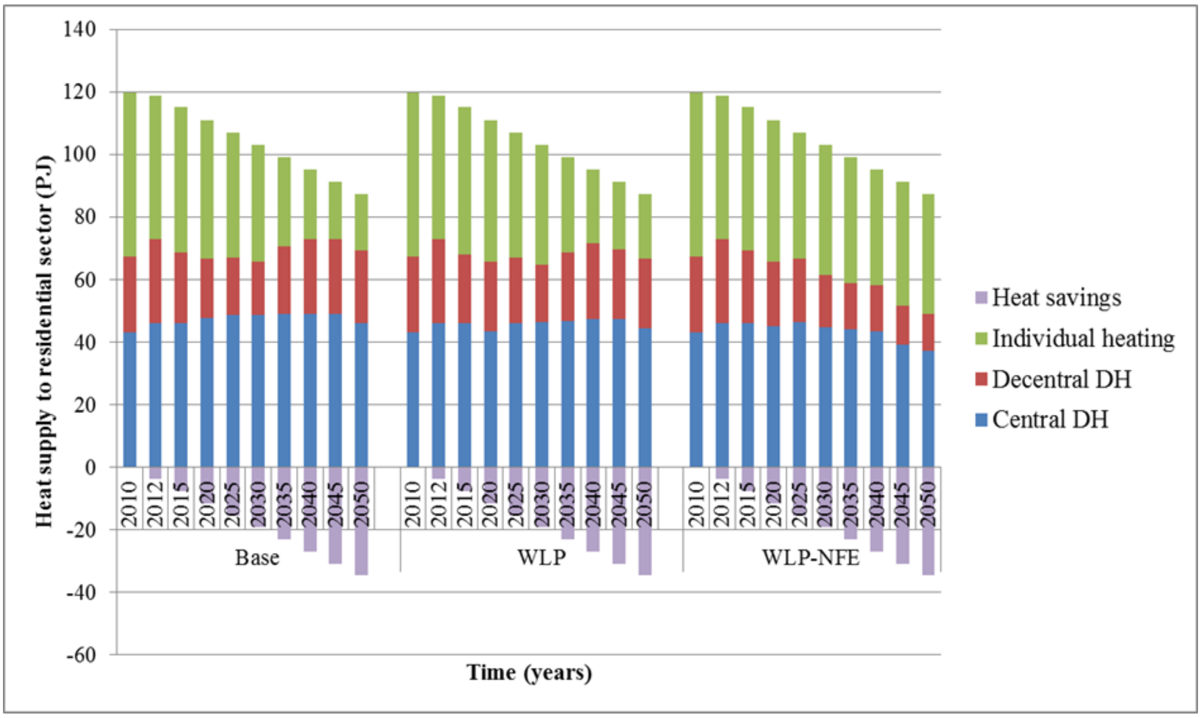

Fig. 1. Heat supply to residential sector

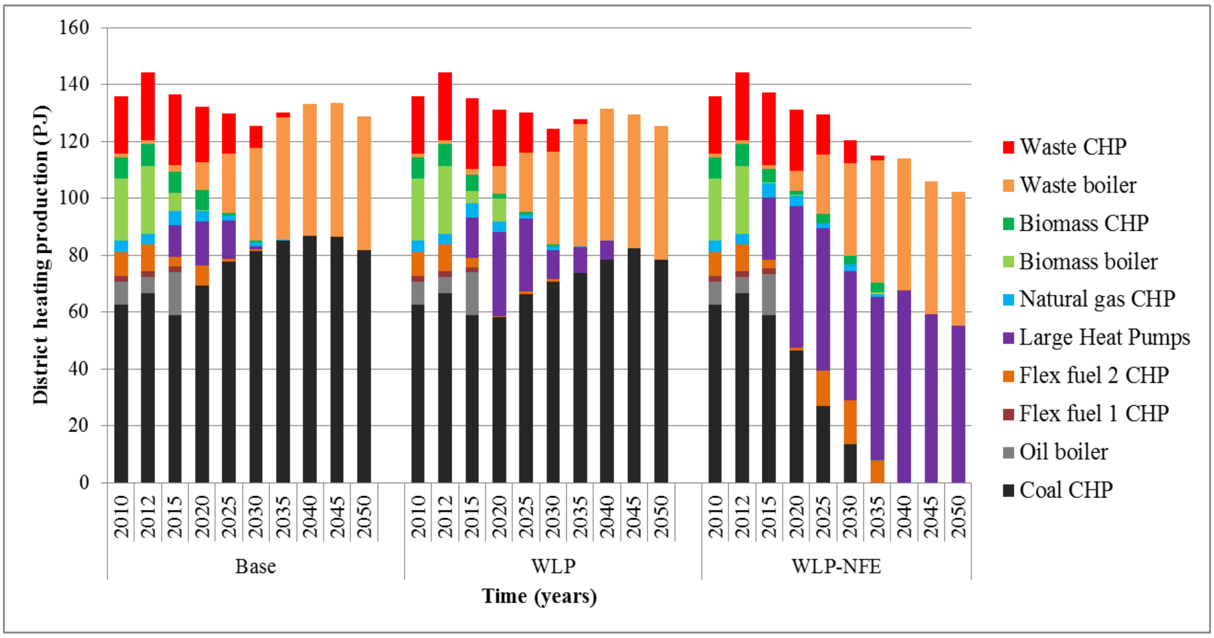

Fig. 2. Production of district heating

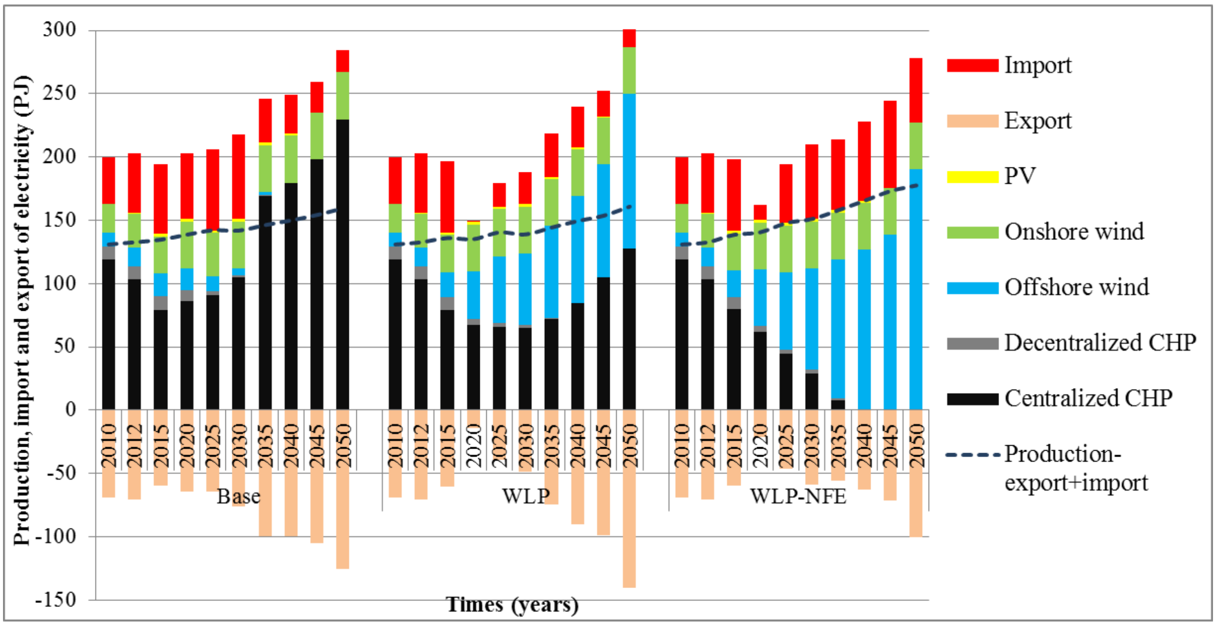

Fig. 3. Production, import and export of electricity

5.2 Costs and environmental emissions

Environmental emissions and the sum of undiscounted system costs for all scenarios until 2050 are presented in Figures 4 and 5, respectively.

Base scenario is characterized by the extensive production of electricity and heat from large centralized coal-based CHPs. It is a mature technology utilising economy of scale and inexpensive fuel. As a result of that investment costs are 7 and 15 % lower than in WLP and WLP-NFE scenario, respectively. In Base scenario, electricity price in Denmark is lower compared to neighbouring countries, so total system costs are reduced by export of electricity. As a result of high production from coal and absence of any emission constraint, high environmental emissions arise in Base scenario.

In WLP scenario, part of the electricity production from coal-based CHPs is substituted by production from offshore wind mills resulting in higher investment costs. On the other hand, less fuel is used in this scenario resulting in lower fuel costs. The total system costs are higher in WLP scenario compared to Base because earnings from export of electricity are 18 % lower. The imposed renewable energy target only affects the fuel use in power and heat sector resulting in lower emissions from this sector while emissions from other sectors remained almost unchanged.

In WLP-NFE scenario, renewable energy constraints were dictating the investments from the beginning of the analysed period. The investments are mainly made in offshore wind, resulting in highest investment and lowest fuel costs compared to other analysed scenarios. The average electricity price is higher than in other scenarios resulting in lower export and thus lower earnings from electricity export. Environmental emissions from power production are reduced starting from 2020, while after 2035 environmental emissions from power and heat production come only from incineration of waste. Transport sector produces emissions all the way until 2050 when is affected by "100 % renewable energy system constraint".

6. Conclusion

TIMES model of the Danish energy system, TIMES-DTU was used to analyse three possible development paths of the Danish energy system until 2050. The results show that if no renewable energy targets are imposed to the model, most of the electricity and heat would be produced in coal-based CHPs. District heating share would reach 73 % of total heat demand in 2050, while 40-50 % of the Danish power production would be exported.

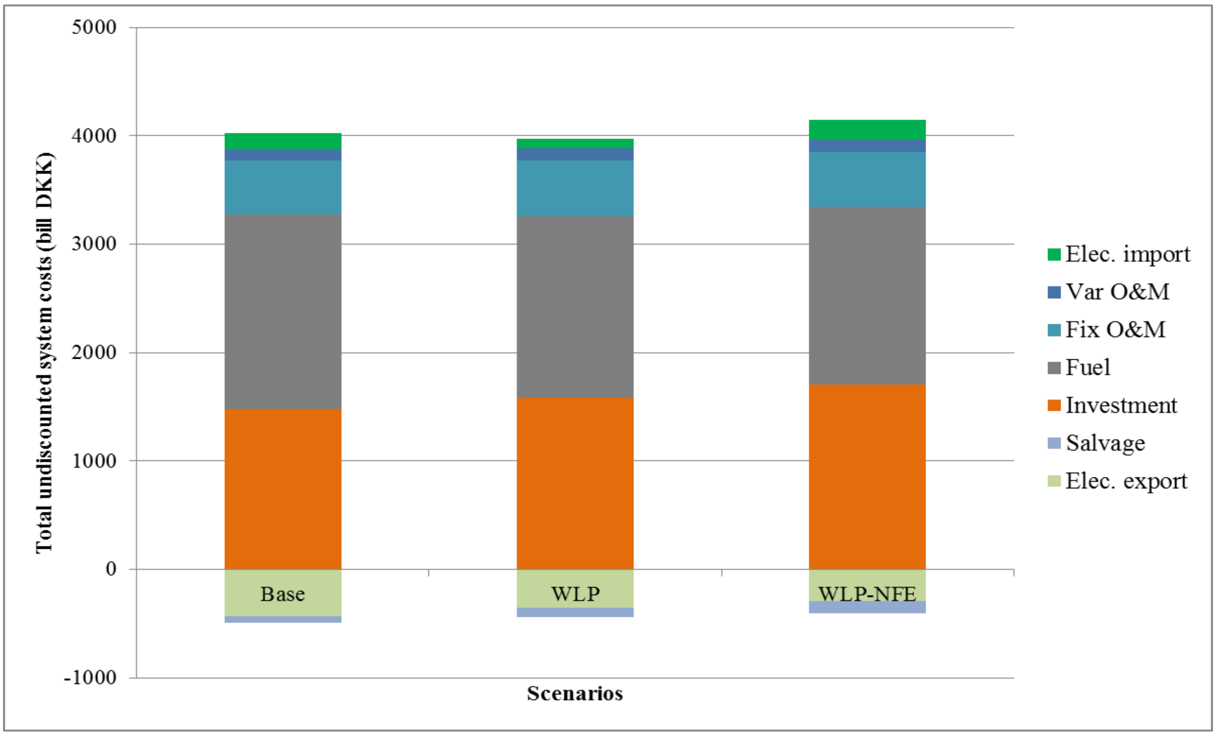

Fig. 4. Undiscounted system costs

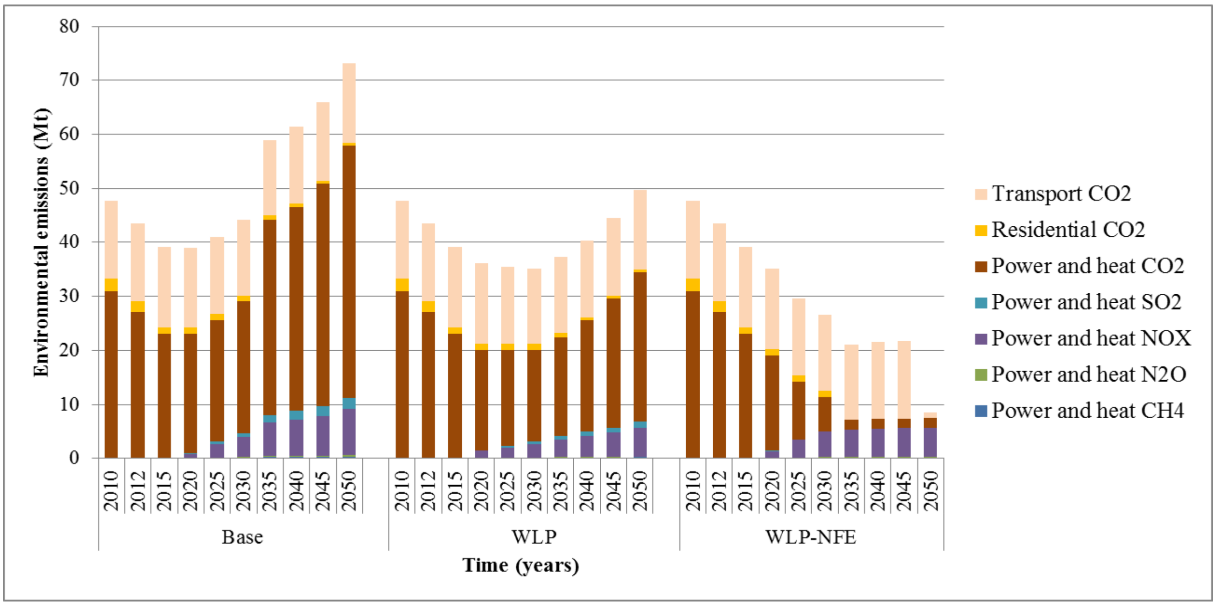

Fig. 5. Environmental emissions from different sectors

Renewable energy target of 50 % of electricity from wind in 2020 forces investments in wind power. Since onshore potentials are not sufficient, investments in offshore wind are necessary. In this scenario, offshore wind makes 43 % of Danish electricity production in 2050. Heat supply is still dominated by district heating based on waste and coal. Denmark still exports significant amounts of electricity. When the use of fossil fuels for production of electricity and heat is forbidden starting from 2035, power production becomes totally reliant on wind power, especially offshore. The district heating production switches from coal-based CHPs to large-scale heat pumps.

Four overall conclusions can be drawn from the analysed scenarios. First, achieving at least 50 % of electricity production from wind power starting from 2020 (WLP scenario) implies less than 1 % higher total system costs compared to Base scenario. Second, achieving fossil fuel free power and heat production starting from 2035 and 100 % renewable energy system starting from 2050 (WLP-NFE scenario) implies 5-6 % higher total system costs compared to Base scenario. Third, heat savings in building stock are important components of the future Danish energy system in all scenarios. Fourth, Denmark has sufficient resources to base its renewable energy supply on domestic resources at reasonable costs.

References

[1] Lund H., Renewable energy systems: the choice and modeling of 100% renewable solutions. Burlington, USA: Academic Press; 2010.

[2] Danish Energy Agency. Energy statistics 2013 – Available at: <http://www.ens.dk/info/tal-kort/statistik-nogletal/arlig-energistatistik> [accessed 26.02.2015] [in Danish].

[3] The Danish Goverment. Energy strategy 2050: from coal, oil and gas to green energy – Available at: <http://www.kebmin.dk/sites/kebmin.dk/files/news/from-coal-oil-and-gas-to-green-energy/Energy%20Strategy%202050%20web.pdf> [accessed 26.02.15].

[4] Münster, M., Morthorst, P. E., Larsen, H. V., Bregnbæk, L., Werling, J., Lindboe, H. H. & Ravn, H. (2012). The role of district heating in the future Danish energy system. Energy, 48(1), 47–55. doi:10.1016/j.energy.2012.06.011

[5] Lund, H., Moller, B., Mathiesen, B. V., & Dyrelund, A. (2010). The role of district heating in future renewable energy systems. Energy, 35(3), 1381–1390. doi:10.1016/j.energy.2009.11.023

[6] Moller, B., Lund, H., 2010. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. Applied Energy 87, 1846–1857. doi:10.1016/j.apenergy.2009.12.001

[7] Nielsen, S., & Moller, B. (2012). Excess heat production of future net zero energy buildings within district heating areas in Denmark. Energy, 48(1), 23–31. doi:10.1016/j.energy.2012.04.012

[8] Østergaard, P. A., Mathiesen, B. V., Möller, B., & Lund, H. (2010). A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy, 35(12), 4892–4901. doi:10.1016/j.energy.2010.08.041

[9] Hedegaard, K., & Münster, M. (2013). Influence of individual heat pumps on wind power integration - Energy system investments and operation. Energy Conversion and Management, 75, 673–684. doi:10.1016/j.enconman.2013.08.015

[10] Hedegaard, K., & Balyk, O. (2013). Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks. Energy, Energy, 63, 356–365. doi:10.1016/j.energy.2013.09.061

[11] Hedegaard, K., Mathiesen, B. V., Lund, H., & Heiselberg, P. (2012). Wind power integration using individual heat pumps – Analysis of different heat storage options. Energy, 47(1), 284–293. doi:10.1016/j.energy.2012.09.030

[12] Sperling, K., & Möller, B. (2012). End-use energy savings and district heating expansion in a local renewable energy system. Applied Energy, 92, 831–842. doi:10.1016/j.apenergy.2011.08.040

[13] Zvingilaite, E. (2013). Modelling energy savings in the Danish building sector combined with internalisation of health related externalities in a heat and power system optimisation model. Energy Policy, 55, 57–72. doi:10.1016/j.enpol.2012.09.056

[14] Zvingilaite, E., & Balyk, O. (2014). Heat savings in buildings in a 100% renewable heat and power system in Denmark with different shares of district heating. Energy and Buildings, 82, 173–186. doi:10.1016/j.enbuild.2014.06.046

[15] Juul, N., & Meibom, P. (2011). Optimal configuration of an integrated power and transport system. Energy, 36(5), 3523–3530. doi:10.1016/j.energy.2011.03.058

[16] Kiviluoma, J., & Meibom, P. (2010). Influence of wind power, plug-in electric vehicles, and heat storages on power system investments. Energy, 35(3), 1244–1255. doi:10.1016/j.energy.2009.11.004

[17] Karlsson, K. B., & Meibom, P. (2008). Optimal investment paths for future renewable based energy systems - Using the optimisation model Balmorel. International Journal of Hydrogen Energy, 33(7), 1777–1787. doi:10.1016/j.ijhydene.2008.01.031

[18] Juul, N., & Meibom, P. (2012). Road transport and power system scenarios for Northern Europe in 2030. Applied Energy, 92, 573–582. doi:10.1016/j.apenergy.2011.11.074
[19] Hedegaard, K., Ravn, H., Juul, N., & Meibom, P. (2012). Effects of electric vehicles on power systems in Northern Europe. Energy, 48(1), 356–368. doi:10.1016/j.energy.2012.06.012
[20] Münster, M., & Meibom, P. (2011). Optimization of use of waste in the future energy system. Energy, 36(3), 1612–1622. doi:10.1016/j.energy.2010.12.070
[21] Münster, M., Ravn, H., Hedegaard, K., Juul N., Ljunggren Söderman, M. (2015). Economic and environmental optimization of waste treatment, Waste Management, Available online 13 January 2015, http://dx.doi.org/10.1016/j.wasman.2014.12.005.
[22] Zvingilaite, E. (2011). Human health-related externalities in energy system modelling the case of the Danish heat and power sector. Applied Energy, 88(2), 535–544. doi:10.1016/j.apenergy.2010.08.007
[23] Mathiesen, B. V., Lund, H., & Karlsson, K. (2011). 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy, 88(2), 488–501. doi:10.1016/j.apenergy.2010.03.001
[24] Mathiesen, B. V., Lund, H., & Connolly, D. (2012). Limiting biomass consumption for heating in 100% renewable energy systems. Energy, 48(1), 160–168. doi:10.1016/j.energy.2012.07.063
[25] Glynn, J., Chiodi, A., Gargiulo, M., Deane, J. P., Bazilian, M., & Gallachóir, B. Ó. (2013). Energy Security Analysis: The case of constrained oil supply for Ireland. Energy Policy, Energy Policy. doi:10.1016/j.enpol.2013.11.043
[26] Chiodi, A., Gargiulo, M., Deane, J. P., Lavigne, D., Rout, U. K., & Gallachoir, B. P. O. (2013). Modelling the impacts of challenging 2020 non-ETS GHG emissions reduction targets on Ireland's energy system. Energy Policy, 62, 1438–1452. doi:10.1016/j.enpol.2013.07.129
[27] Chiodi, A., Gargiulo, M., & Rogan, F. (2013). Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system. Energy Policy, 53, 169.
[28] Welsch, M., Deane, P., Howells, M., Gallachoir, B. O., Rogan, F., Bazilian, M., & Rogner, H.-H. (2014). Incorporating flexibility requirements into long-term energy system models - A case study on high levels of renewable electricity penetration in Ireland. Applied Energy, 135, 600–615. doi:10.1016/j.apenergy.2014.08.072
[29] Merkel, E., Fehrenbach, D., McKenna, R., & Fichtner, W. (2014). Modelling decentralised heat supply: An application and methodological extension in TIMES. Energy, 73, 592–605. doi:10.1016/j.energy.2014.06.060
[30] Fehrenbach, D., Merkel, E., McKenna, R., Karl, U., & Fichtner, W. (2014). On the economic potential for electric load management in the German residential heating sector - An optimising energy system model approach. Energy, 71, 263–276. doi:10.1016/j.energy.2014.04.061
[31] Blesl, M., Das, A., Fahl, U., & Remme, U. (2007). Role of energy efficiency standards in reducing CO2 emissions in Germany: An assessment with TIMES. Energy Policy, 35(2), 772–785. doi:10.1016/j.enpol.2006.05.013
[32] Fais, B., Blesl, M., Fahl, U., & Voß, A. (2014). Analysing the interaction between emission trading and renewable electricity support in TIMES. Climate Policy, Clim. Policy. doi:10.1080/14693062.2014.927749
[33] Lind, A., Rosenberg, E., Seljom, P., Espegren, K., Fidje, A., & Lindberg, K. (2013). Analysis of the EU renewable energy directive by a techno-economic optimisation model. Energy Policy, 60, 364–377. doi:10.1016/j.enpol.2013.05.053
[34] Rosenberg, E., Lind, A., & Espegren, K. A. (2013). The impact of future energy demand on renewable energy production - Case of Norway. Energy, 61, 419–431. doi:10.1016/j.energy.2013.08.044
[35] Kannan, R., & Turton, H. (2012). Cost of ad-hoc nuclear policy uncertainties in the evolution of the Swiss electricity system. Energy Policy, 50, 391–406. doi:10.1016/j.enpol.2012.07.035
[36] Maizi, N., & Assoumou, E. (2014). Future prospects for nuclear power in France. Applied Energy, 136, 849–859. doi:10.1016/j.apenergy.2014.03.056

[37] ETSAP homepage – Available at: <http://www.iea-etsap.org/web/index.asp. [accessed 26.02.15]
[38] Labriet, M., & Loulou, R. (2008). ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure. Computational Management Science, 5(1-2), 7-40. doi:10.1007/s10287-007-0046-z
[39] Loulou, R. (2008). ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation. Computational Management Science, 5(1-2), 41-66. doi:10.1007/s10287-007-0045-0
[40] Documentation of ETSAP modelling tools. http://www.iea-etsap.org/web/documentation.asp [accessed 26.02.15]
[41] Overview of TIMES Modelling Tool http://www.iea-etsap.org/web/Times.asp [accessed 20.09.15]
[42] RISØ DTU & Ea Energianalyse (2010). Future scenarios and measures, Sector Analysis - Electricity and heat supply – Available at: <http://www.ens.dk/sites/ens.dk/files/politik/dansk-klima-energipolitik/klimakommissionen/groen-energi/baggrundsrapporter/Sektoranalyse_el_og_varmeforsyning.pdf> [accessed 20.09.14] [in Danish]
[43] Danish Commission on Climate Change Policy (2010). Green energy - the road to a Danish energy system without fossil fuels – Available at: <http://www.ens.dk/politik/dansk-klima-energipolitik/klimakommissionen/gron-energi> [accessed 26.02.15] [in Danish]
[44] Danish Energy Agency (DEA) (2014). Energy Scenarios towards 2020, 2035 and 2050 – Available at: http://www.ens.dk/sites/ens.dk/files/dokumenter/publikationer/downloads/energiscenarier_-_analyse_2014_web.pdf [accessed 26.02.15] [in Danish]
[45] Andersen, F. M., & Larsen, H. V. (2012). FRIDA: A model for the generation and handling of solid waste in Denmark. Resources, Conservation and Recycling, Resour. Conserv. Recycl, 65, 47–56. doi:10.1016/j.resconrec.2012.04.004
[46] Ea Energy Analyses (2013) Analysis of biomass prices - Future Danish Prices for Straw, Wood Chips and Wood Pellets.
[47] Ea Energy Analyses (2014). Update of fossil fuel and CO2 price projection assumptions - Convergence Pathway.
[48] Energinet.dk (2014). Energinet.dk's analysis assumptions 2014 – 2035 – Available at: http://energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Energinet%20dks%20analyseforuds%C3%A6tninger%202014-2035%20maj%202014%20final.pdf[accessed 26.02.15]
[49] Danish Energy Agency (DEA) (2013). Energy producers count 2010-2012.
[50] Danish Energy Agency (DEA) (2014). Register of wind turbines.
[51] Danish Energy Agency (DEA) (2013). Technology Data for Energy Plants - Individual Heating Plants and Energy Transport.
[52] Danish District Heating Association (2012). Annual district heating statistics 2011/2012,
[53] Ministry of Housing, Urban and Rural Affairs (2014). BBR dataset
[54] Petrovic, S., & Karlsson, K. (2014) Model for Determining Geographical Distribution of Heat Saving Potentials in Danish Building Stock. ISPRS International Journal of Geo-Information, 3(1), 143-165. doi:10.3390/ijgi3010143
[55] Petrovic, S., & Karlsson, K. B. (2014). Danish heat atlas as a support tool for energy system models. Energy Conversion and Management, 87, 1063-1076.
[56] Danish Energy Agency (2012). Danish energy projections 2012.
[57] Danish Ministry of Climate, Energy and Buildings. The Governments' energy and climate political objectives and the results of the energy agreement in 2020 – Available at: <http://www.kebmin.dk/files/klima-energi-bygningspolitik/dansk-klima-energi-bygningspolitik/energiaftale/Faktaark%202%20energi%20og%20klimapolitiske%20mal.pdf> [accessed 26.02.15] [in Danish].
[58] The Danish Government. Our energy – Available at: <http://www.ens.dk/politik/dansk-klima-energipolitik/regeringens-klima-energipolitik/vores-energi> [accessed 26.02.15] [in Danish].